Preprint
UCRL-JC-141557

Biogeochemical Proxies in Scleractinian Corals used to Reconstruct Ocean Circulation

T.P. Guilderson, M. Kashgarian and D.P. Schrag

This article was submitted to
Conference on the Study of Environmental Changes Using Isotope Techniques, Vienna, Austria, April 23-27, 2001

U.S. Department of Energy

Lawrence
Livermore
National
Laboratory

February 23, 2001

Biogeochemical proxies in scleractinian corals used to reconstruct ocean circulation

Thomas P. Guilderson[1,2], Michaele Kashgarian[1], and Daniel P. Schrag[3]

1. Center for Accelerator Mass Spectrometry, UC/LLNL L-397, 7000 East Avenue, Livermore CA 94551, USA.

2. Department of Ocean Sciences, University of California - Santa Cruz, 1156 High Street, Santa Cruz CA 95064, USA.

3. Laboratory for Geochemical Oceanography, Department of Earth and Planetary Sciences, Harvard University, 20 Oxford Street, Cambridge MA 02138, USA.

To be presented at:

Conference on the Study of Environmental Changes Using Isotope Techniques
Vienna, Austria
23 to 27 April 2001.

Abstract

We utilize monthly ^{14}C data derived from coral archives in conjunction with ocean circulation models to address two questions: 1) how does the shallow circulation of the tropical Pacific vary on seasonal to decadal time scales and 2) which dynamic processes determine the mean vertical structure of the equatorial Pacific thermocline. Our results directly impact the understanding of global climate events such as the El Ni o-Southern Oscillation (ENSO). To study changes in ocean circulation and water mass distribution involved in the genesis and evolution of ENSO and decadal climate variability, it is necessary to have records of climate variables several decades in length. Continuous instrumental records are limited because technology for continuous monitoring of ocean currents has only recently been available, and ships of opportunity archives such as COADS contain large spatial and temporal biases. In addition, temperature and salinity in surface waters are not conservative and thus can not be independently relied upon to trace water masses, reducing the utility of historical observations. Radiocarbon (^{14}C) in sea water is a quasi-conservative water mass tracer and is incorporated into coral skeletal material, thus coral ^{14}C records can be used to reconstruct changes in shallow circulation that would be difficult to characterize using instrumental data. High resolution $\Delta^{14}C$ timeseries such as these, provide a powerful constraint on the rate of surface ocean mixing and hold great promise to augment onetime surveys such as GEOSECS and WOCE. These data not only provide fundamental information about the shallow circulation of the Pacific, but can be used as a benchmark for the next generation of high resolution ocean models used in prognosticating climate change.

1. Overview

Instrumental and climate proxy records document an increase in surface temperatures over the last ~125 years[1] as well as a recent change in the frequency and intensity of El Ni o - Southern Oscillation (ENSO) events[2,3]. A fundamental question is whether or not the observed variation in climate characteristics such as temperature or El Ni o frequency is a consequence of human activities or natural variability. To study changes in ocean circulation and water mass distribution involved in the genesis and evolution of ENSO and decadal climate variability, it is necessary to have records of climate variables such as sea surface temperature or precipitation several decades in length. Such records do not currently exist because technology for continuous monitoring of ocean currents (eg. satellites and buoy arrays) have only recently been available and historical observations (ships of opportunity) have large spatial and temporal gaps.

We have focussed our research toward two primary goals: the first is a better quantification and documentation of the redistribution of surface waters in the tropical and sub-tropical Pacific and the second is a better understanding of the sources of the water which upwells in the equatorial Pacific. In a zonally averaged and simplified sense, there exists an upper oceanic Hadley Cell in the Pacific: subduction occurs in the sub-tropics during the winter season and this water ventilates the tropical thermocline where it upwells and returns to the subducting regions through surface flow[4]. These questions are important because modeling studies have shown that changes in the thermal structure of the equatorial thermocline can influence decadal variability of ENSO. In fact, of all the parameter sensitivity studies which have been conducted with the coupled Zebiak and Cane model, changing the temperature structure of the thermocline has the strongest influence on model behavior[5]. Building on observational evidence of Deser et al.,[6] it has been hypothesized that temperature anomalies originating at the sea-surface in the northern hemisphere subtropics can be propagated via this sub-surface pathway and interact with the equatorial thermocline, changing the character and sensitivity of ENSO[7,8]. Tritium and ^{3}He tracer data indicate that the ventilation time-scale of the tropical thermocline is on the order of decades[9]. It is a logical extension to hypothesize that the intergyre exchange between the subtropical subduction zones and the tropical thermocline could determine the decadal-scale climate character of the tropical Pacific.

1.1 Oceanographic Setting

The tropical ocean-atmosphere system exhibits a systematic and relatively irregular interannual variability, the dominant mode of which is the atmosphere s Southern Oscillation and its ocean companion, El Ni o[10]. The tropical ocean and atmosphere are intimately coupled through the interaction of the surface winds and the underlying SST field. The mean southeasterly trade winds combined with surface heating results in a buildup of warm surface water in the western tropical Pacific, the Pacific warm pool. The accumulation of warm water at the western margin of the Pacific Ocean drives tropospheric circulation by creating deep convection aloft. In the east, the trade winds induce shoaling of the thermocline and outcropping of colder isotherms, primarily of the Equatorial Under Current. This east-west sea surface temperature (SST) gradient is accompanied by a concommitant sea-height slope of several 10s of centimeters and a basin-wide slope to the thermocline: deeper in the west and shallower in the east. When the trade winds relax or even fail, the warm water normally constrained to the western margin migrates back down the geopotential slope. At such time the normally cold eastern equatorial Pacific is warmer than normal due to a reduction or even cessation of upwelling and a deepening of the thermocline. Indonesia (and Australia) experiences drought whereas the normally arid central equatorial Pacific may receive several meters of rain (Figure 1). Corresponding changes also occur under the South Pacific Convergence Zone and the inter-tropical convergence zone in the eastern Pacific.

Contemporary research has determined relationships or patterns associated with the displacement of the major convective centers such as the Indonesian Low. Variations in the location and intensity of the Indonesian Low impacts the redistribution of sensible and latent heat as well as potential precipitable water within the atmosphere . This "wholesale" redistributionaffects the structure of the planetary waves and thus is able to orchestrate far-field temperature and precipitation responses. In this fashion, the tropical Indo-Pacific is linked to the extra-tropics in both hemispheres via teleconnections.

1.2 Radiocarbon in the Ocean

The distribution of radiocarbon (^{14}C) in the surface ocean is a sensitive indicator of ocean circulation. Radiocarbon is produced in the stratosphere by the collision of nitrogen atoms with thermal neutrons produced naturally by cosmic rays or artificially by atmospheric nuclear bomb testing. Atomic ^{14}C is rapidly oxidized to $^{14}CO_2$ in the atmosphere and is introduced into the surface ocean via gas exchange. The flux of radiocarbon to the deep ocean is accomplished by convective processes, and by settling of particulate matter. Because the residence time of water in the deep ocean is long enough to allow for significant radioactive decay (^{14}C half-life = 5730 y), the deep ocean is depleted in ^{14}C relative to the surface ocean. This contrast makes the distribution of radiocarbon in the surface ocean particularly sensitive to vertical mixing and subsequent lateral exchange.

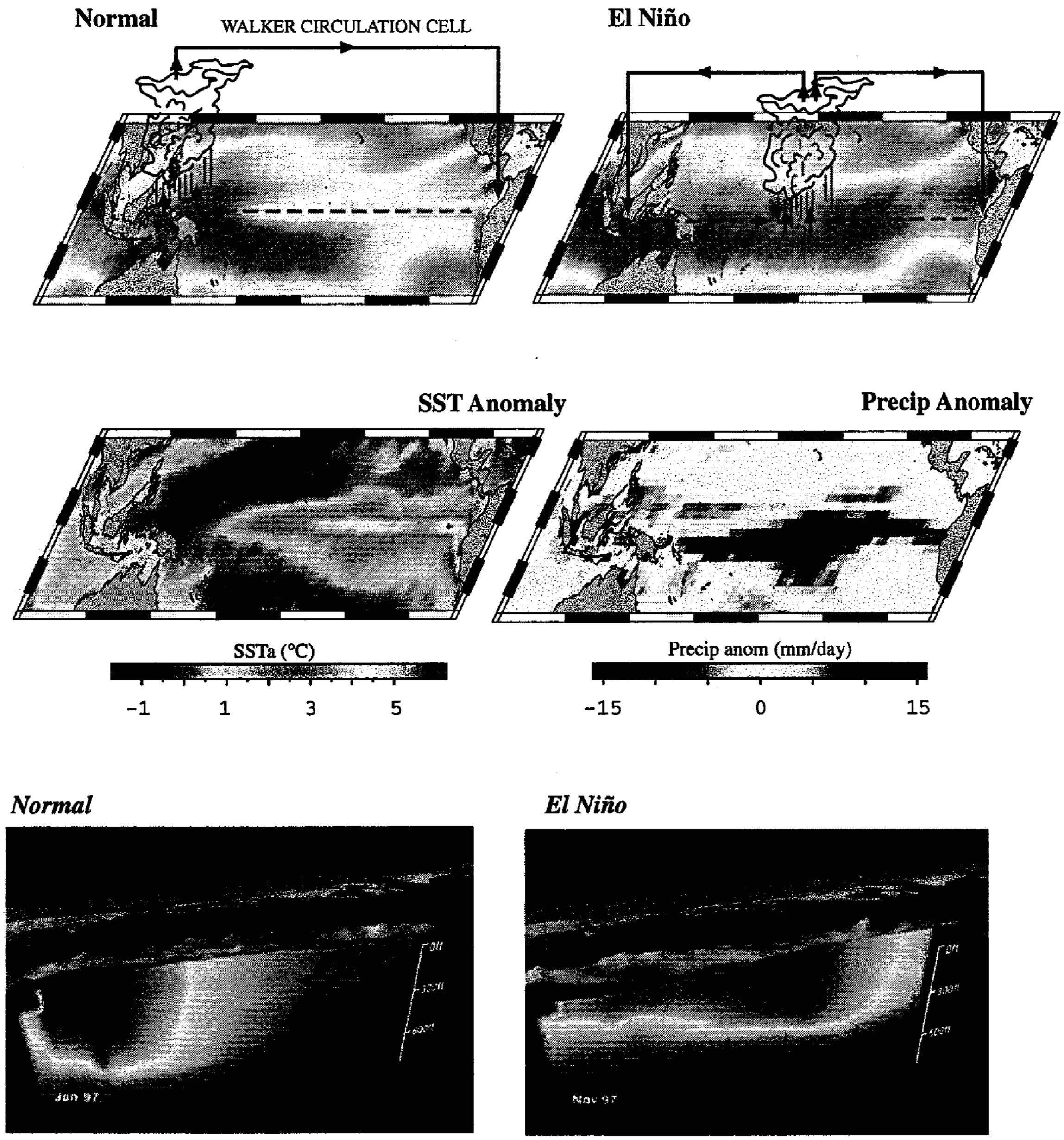

Figure 1. A schematic of the nature of the coupled tropical ocean-atmosphere system. Upper panels depict non-El Ni o (normal or La Ni a) precipitation and sea surface temperatures (left) and El Ni o conditions (right). Warm water in the western equatorial Pacific localizes deep convection which exports latent and sensible heat to both hemispheres. The corresponding winds have both a meridional (Hadley Cell) and zonal (Walker Circulation) component, which includes the surface trade winds. Middle panels are the respective SST and precipitation anomalies observed during the 1982/1983 ENSO. Lower panel is equatorial subsurface data from the TOGA/TAO array (courtesy of PMEL, NOAA) and exemplifies the shift in thermocline tilt and depth during an ENSO cycle that conspires to suppress upwelling in the eastern equatorial Pacific.

Since the 1950s, excess production of ^{14}C from nuclear weapons testing and its subsequent invasion into the surface ocean has augmented the difference between the surface and the deep ocean. Over this time frame radioactive decay and biological processes have minimal impact on surface water ˘^{14}C, and as a consequence ˘^{14}C is a quasi-conservative tracer which effectively tags water masses. The use of ^{14}C as a global ocean circulation tracer was a primary objective of the study of the distribution of natural and bomb-produced ^{14}C in the Geochemical Ocean Sections Study (GEOSECS) of the 1970s[11] and of the present day World Ocean Circulation Experiment (WOCE[12]). Radiocarbon measurements of coral skeletal material which accurately records ˘^{14}C of ΣCO_2[13,14] have added important information to water sampling programs. The ^{14}C in the coral aragonite skeleton reflects seawater radiocarbon content at the time of deposition and as such measurements in corals make it possible to reconstruct the radiocarbon content of the surface ocean back to pre-bomb and pre-industrial values[13,14]. High-resolution coral-based time-series have clearly identified a time-varying surface water gradient of post-bomb ^{14}C from the equator toward the temperate latitudes with a total dynamic range in excess of 220 . The distribution represents upwelling of low ^{14}C water from the lower thermocline in equatorial regions, with migration of the ^{14}C rich surface water toward higher latitudes. Using coral time-series we have demonstrated that for the surface ocean, where radiocarbon gradients are highest and transport is rapid that temporal variability is of the same order as spatial variability a fact lost in discrete analyses like GEOSECS or WOCE.

2. Analytical Methods

After identifying both in terms of an oceanographically significant context, and potential quality (eg. length, continuity) of the potential coral record, the coral is cored with an underwater drilling apparatus. Coral cores (nominally 8mm diameter) are cut into ~1cm slabs, cleaned in distilled water, and air-dried. Visual inspection is performed to identify regions infilled or disturbed by boring organisms. X-radiographs are taken in order to clarify the skeletal architecture and to document density variations. After identifying the major vertical growth axis, the coral is sequentially sampled at 1-mm (or 2-mm) increments with a low-speed drill. Splits (~1 mg) are reacted in vacuo in a modified common acid-bath autocarbonate device at 90¡C and the purified CO_2 analyzed on a gas source stable isotope ratio mass spectrometer (–0.05 1-σ). Strontium to calcium ratios are also determined on ~1mg splits using an inductively coupled plasma atomic emission mass spectrometer (ICP-AES) following the methodology of Schrag[15]. Analytical precision based on an in-house homogenized coral standard is –0.2% equivalent to ~0.3¡C.

For the data that we have generated, the remaining sample splits (nominally 8-10 mg) are placed in individual reaction chambers, evacuated, heated, and then acidified with orthophosphoric acid at 90¡C. The evolved CO_2 is purified, trapped, and converted to graphite in the presence of cobalt catalyst in individual reactors[16]. Graphite targets were measured at the Center for Accelerator Mass Spectrometry, LLNL[17]. Radiocarbon results are reported as age-corrected $\Delta^{14}C$ ( ) as defined by Stuiver and Polach[18].

Coral chronology has historically relied upon the presence of annual high- and low-density band couplets[19] or the seasonal variability in coral $\delta^{13}C$ which has been interpreted to reflect surface irradiance[20]. Independent chronologies based on these two methods on the same coral specimen tend to agree within a few to 6 months[21]. Such an age-model is not adequate for high-resolution $\Delta^{14}C$ records where one of the ultimate goals is to compare the observed time-series and those simulated in high-resolution ocean models. We create a preliminary age-model using sclerochronology (ie. banding) and $\delta^{13}C$ variations, but in order to obtain the best timescale and because we are not interested in the coral $\delta^{18}O$ and [Sr/Ca] as an independent measure of temperature[15], we refine our age-models by correcting the preliminary age-model through $\delta^{18}O$ and [Sr/Ca] comparisons with instrumental records of SST and or precipitation (Figure 2). Because the oxygen isotopic composition of the coral responds to not only temperature but salinity, or more accurately $\delta^{18}O_w$ variations, it is necessary to use both the $\delta^{18}O_{coral}$ and $[Sr/Ca]_{coral}$ data to derive an accurate age-model depending on the phasing of the local SST and salinity (precipitation) seasonal cycle. In fast growing corals where there is strong seasonality in either precipitation and or temperature, the corresponding age-model can have an error on the order of –1 month.

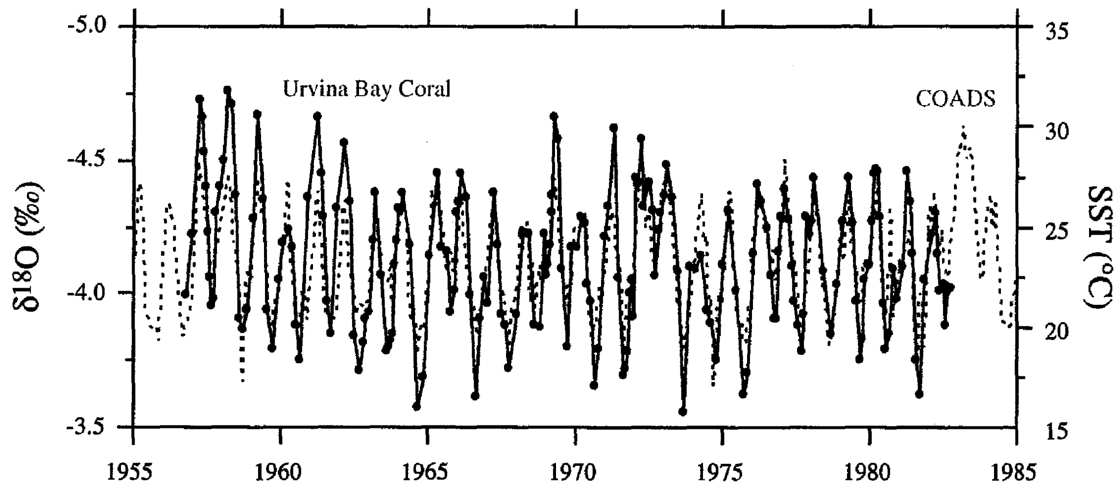

Figure 2. Refined coral chronology through the use of $\delta^{18}O$ and available instrumental data. A preliminary $\delta^{13}C$ - sclerochronology model was created and then optimized by matching peaks and troughs in $\delta^{18}O$ corresponding to SST, and to some extent salinity variations[15].

3. Coral Time-series Results and Discussion

Corals act like strip-recorders continuously recording the radiocarbon content of the waters in which they live and thus it is possible to use records derived from these biogenic archives to study lateral mixing[22] and vertical exchange processes[23,24]. Although the idea of using corals as recorders of the ^{14}C content of waters is not new, our application of sub-annual multi-decadal studies is novel. Previous coral-based studies tended to be based on annual and bi-annual sampling[13,14], or a few-years of sub-annual samples[25]. This difference in part due to the advantages afforded by accelerator mass spectrometry (throughput, and sample size) and the foreknowledge that in order to study seasonal dynamic processes (eg. upwelling or winter-time Ekman pumping) that coarse sampling could bias or miss the desired signal. We use sub-annually resolved records to gain a window into subsurface processes when our site is chosen for this purpose.

Our work in the Pacific has focussed on sites within the equatorial wave-guide, the extra-tropics, and most recently the Indonesian region (Figure 3). In a general sense, one can think of the sea-surface temperature as reflecting $\Delta^{14}C$. The upwelling in the eastern tropical Pacific exposes water from the equatorial undercurrent, a subsurface water mass that flows west to east bounded approximately by the 24 and 26 potential density surfaces (isopycnals, $kg\text{-}m^{-3}$). This water is derived from subduction of surface water in the sub-tropics and water entrained from greater depths in the tropical thermocline. The sub-tropics water brings higher bomb-produced ^{14}C levels from the sea surface down into the undercurrent. The entrained component mixes colder, low-^{14}C water into the undercurrent, and augments the contrast in

˘^{14}C between the undercurrent and the sea surface. This water is then advected to the warm pool where it mixes with high ^{14}C water from the subtropics.

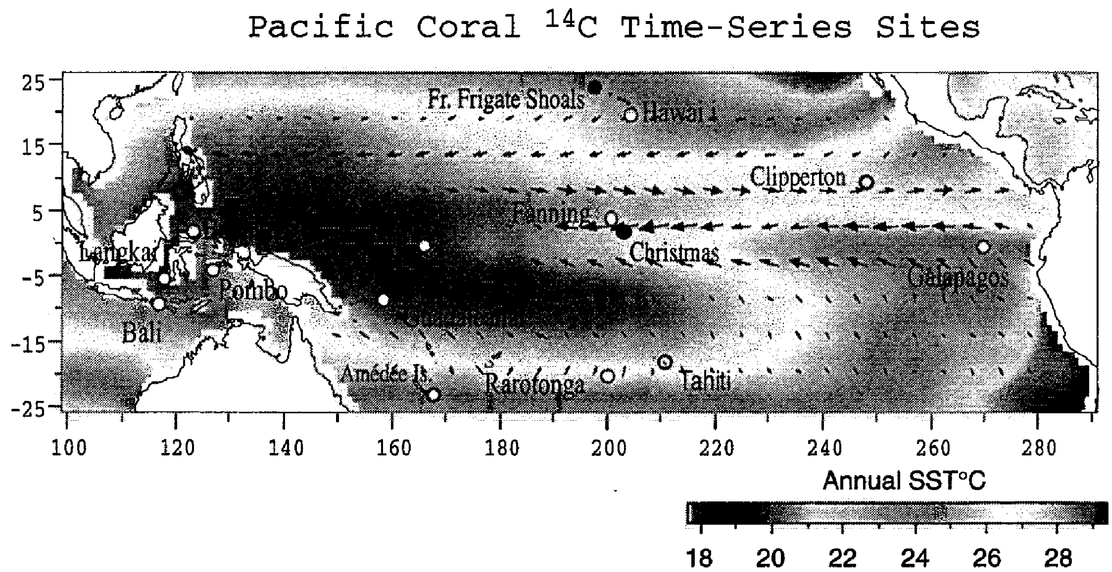

Figure 3. Location of coral sites where we or others are actively working on developing 14C time-series. Mean annual sea surface temperature and general surface current pattern is also shown.

High resolution coral ˘^{14}C studies by Moore et al.,[26] and Guilderson et al.,[22] demonstrate the utility of ^{14}C time series in corals to study the dynamics of ocean circulation over multi-decadal time scales. Our continued objective is to document ^{14}C variability in the surface ocean in the Pacific by making measurements on additional coral samples, and to determine how that variability relates to shallow circulation and mean vertical structure of the tropical Pacific. We have completed post-bomb (~1950 to present) time series from Nauru (166¡E 0.5¡S) and Guadalcanal (167¡E, 7¡S) in the western tropical Pacific; Rarotonga (21¡S, 160¡W) and the Big Island of Hawai i (20¡N, 156¡W) in the subtropics; and a multi-decadal record from Galapagos (90¡W, 0¡) in the eastern equatorial Pacific (Figure 4). In general, the subtropics (Rarotonga, Hawai i) have higher ˘^{14}C reflecting longer mean residence time of surface water in the gyres and higher air-sea exchange. ˘^{14}C in eastern equatorial Pacific surface waters (Galapagos) are lower and due to the subsurface pathway of the Equatorial Undercurrent and entrainment of deeper thermocline waters which feed the upwelling in this region. Radiocarbon values in the warm pool region (Nauru, Guadalcanal) are intermediate between the higher subtropics and those in the east.

Our data show both the long-term increases in ˘^{14}C reflecting oceanic uptake of bomb derived ^{14}C and high amplitude seasonal to interannual variations associated with changes in circulation. The post-bomb ˘^{14}C maxima in the subtropics occurs in the early 1970s whereas at Nauru, Guadalcanal, and Galapagos it is delayed by 10 years. The delay is a consequence of the subsurface history of waters upwelling in the east and the subsequent advection and mixing of this water in the west. Superimposed upon these long-term trends is seasonal to interannual variability, which reflects ocean dynamic processes. At Nauru and Guadalcanal these high amplitude variations reflect the cross-basin advection of surface waters in the tropical Pacific in conjunction with ENSO whereas the Galapagos ˘^{14}C record reflects variations in upwelling intensity. Variability in the subtropics primarily reflects vertical exchange concomitant with winter-time Ekman pumping.

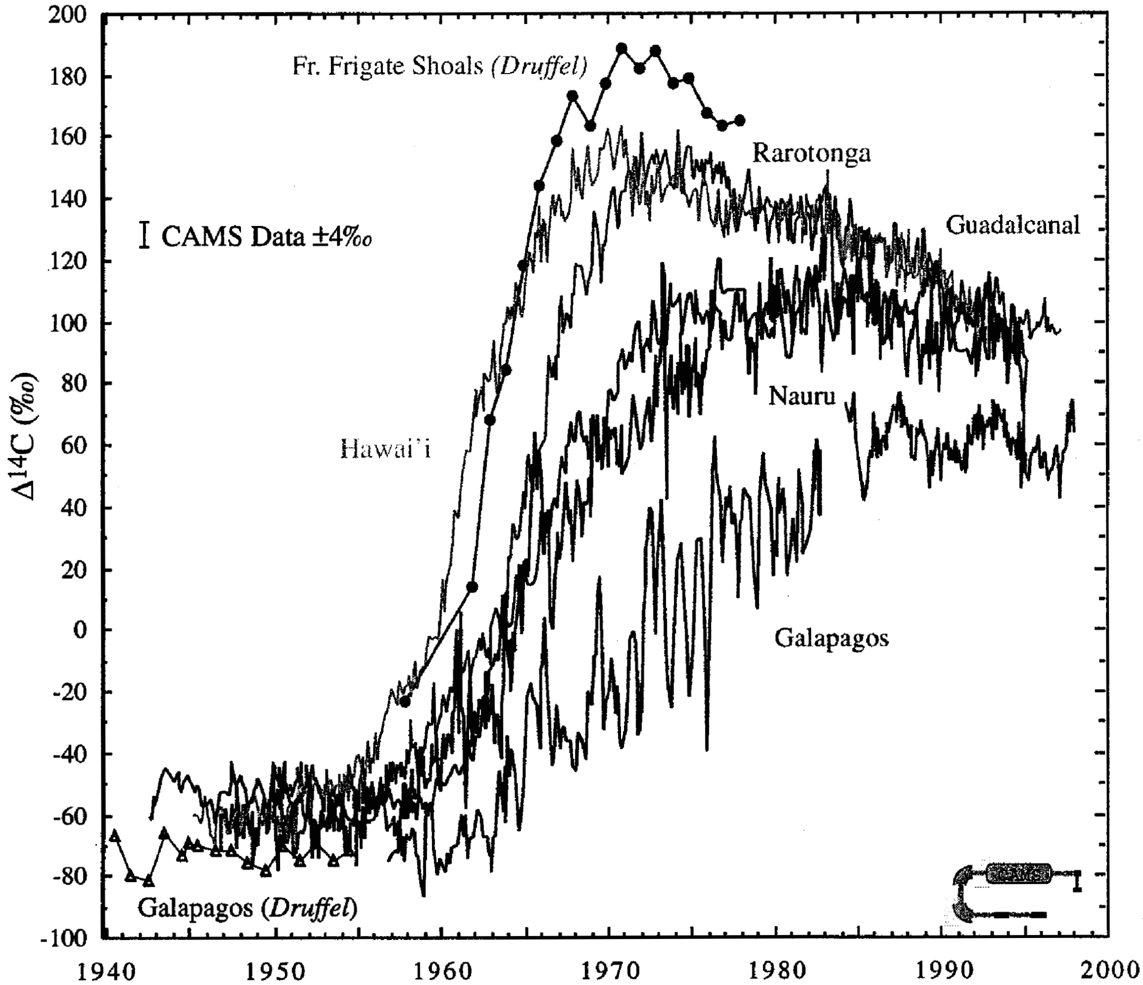

Figure 4. High-resolution coral-based Δ14C timeseries in the Pacific reflect the invasion of bomb-14CO2 (slow trend) and ocean dynamic processes (higher frequency variations).

Our own work on corals from the tropical Pacific is best illustrated using a coral record from Nauru Island. The temporal variability in the coral from Nauru is comparable to the spatial variability from tropics to mid-latitudes described by WOCE and GEOSECS. The temporal variability at Nauru is not a local or coastal signal due to upwelling around the island as it does not correlate with seasonal changes in wind stress that might drive coastal or island-induced upwelling. If upwelling near coastlines were an important effect, this would require that large volumes of water enter the mixed layer from great depths (i.e. lower thermocline), as vertical gradients in radiocarbon are relatively small above the thermocline. Since air-sea isotopic equilibration (gas exchange) occurs too slowly to account for large variability over time scales shorter than one year (it is roughly an order of magnitude slower than the seasonal cycle), a dynamical process internal to the ocean must be responsible.

The general pattern of interannual radiocarbon variability is strongly associated with ENSO, as seen in the comparison with the Ni o-3 index (Figure 5). During ENSO warm events (including during the pre-bomb period), the $^{-14}$C value at Nauru increases, and continues to rise for several months this is followed by a large and rapid decrease, and then a return to mean values. In a simple sense, this pattern can be understood from a conceptual model of ENSO. As a warm event begins, the upwelling of deep, radiocarbon-poor water from the upper thermocline is diminished, causing an increase in $\Delta^{14}C$ in the eastern pacific. Amplifying this factor, the transport time of eastern Pacific water to the Nauru site is longer as tradewinds decrease in strength, allowing for more invasion of bomb-radiocarbon from the atmosphere. If westerlies develop along the equator at the western margin, this will mix in off-equatorial waters with much higher radiocarbon content, also causing an increase in $\Delta^{14}C$ values at Nauru. The large drops in $\Delta^{14}C$ following the ENSO warm events are consistent with the re-establishment of the tropical waveguide following an El Nino event. In this situation one expects an increase in upwelling, and an increase in the strength of westward-flowing currents, basically bringing more water with lower radiocarbon into the eastern Pacific sea surface, and then transporting that water more rapidly to the west with less time to exchange with the atmosphere.

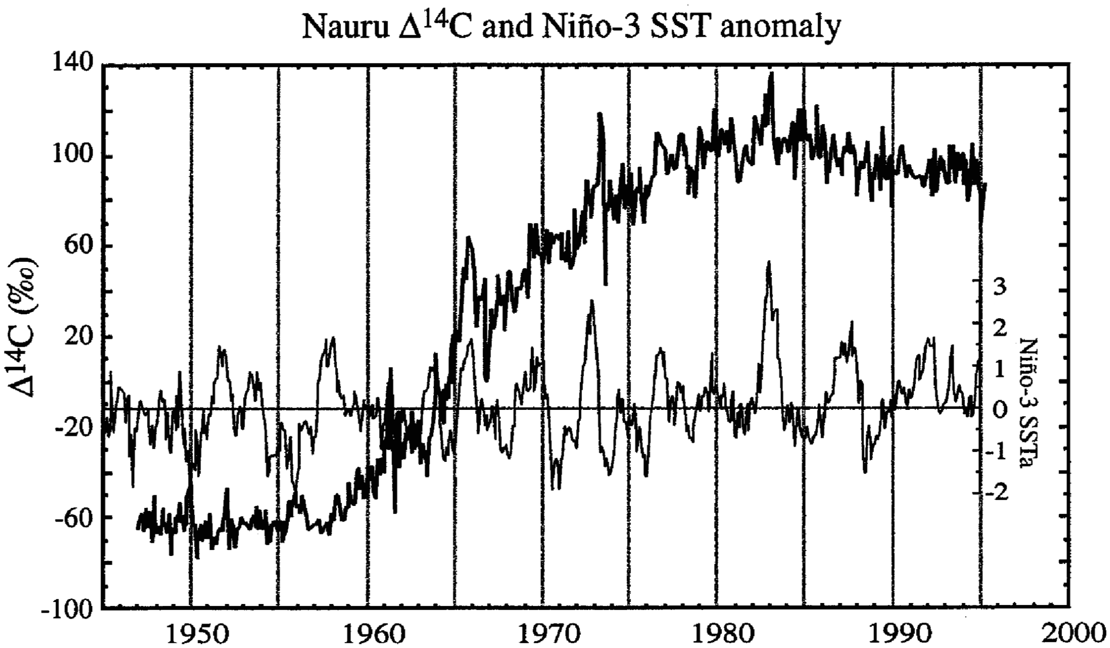

Figure 5. $\Delta^{14}C$ time-history from Nauru Island in the Western Equatorial Pacific and the Nino-3 SST anomaly index. Interannual variability at Nauru reflects a redistribution of surface waters in concert with ENSO. During an El Nino event, equatorial tradewinds slacken which reducd the amount of low-14C eastern equatorial Pacific water advected into the warm pool region. In addition the reduction in sea surface height affords increased infiltration by higher-14C northern subtropic surface waters.

4. Future Directions and Impact

The tracer data that we generate can identify specific changes in the shallow circulation that occurred prior to the implementation of moored arrays instituted in the mid 1980s, and would be difficult to characterize with existing instrumental data. An obvious extension of studies such as those briefly documented here is to constrain fractions of water-masses mixing in a particular region, or with into particular water-mass.

In addition, comparison of model results with observations of radiocarbon and other tracers is an effective way to identify problems or deficiencies in models, and ultimately leads to improved modeling skill[27,28] particularly with respect to vertical exchange processes which are relatively poorly represented in most ocean models. Thus although the data provides fundamental information on the shallow circulation in and by itself, the true strength is a combined approach which is greater than the individual parts; the data helps uncover deficiencies in ocean circulation models and the model results place long $\Delta^{14}C$ time series in a dynamic framework which helps to identify those locations where additional observations are most needed. The time history of $\Delta^{14}C$ is a direct record of the invasion of fossil fuel CO_2 and bomb ^{14}C into the oceans. Therefore the $\Delta^{14}C$ data that are produced in studies such as ours can be used to study the ocean uptake of fossil fuel CO_2 in coupled ocean-atmosphere models[28,29].

Acknowledgements: This work was supported by a CAMS minigrant, and grants to M. Kashgarian and T. Guilderson (LLNL 98-ERI-002) and to D. Schrag from NSF's program in Physical Oceanography (OCE-9796253). Radiocarbon analyses were performed under the auspices of the U.S. Department of Energy by the University of California Lawrence Livermore National Laboratory (contract W-7405-Eng-48).

References:

1. Mann, M. E., R. S. Bradley, and M. K. Hughes, 1998. Global-scale temperature patterns and climate forcing over the past six centuries, *Nature*, ***392***, 779-787.
2. Trenberth, K.E., and Hoar, T.J., 1996. The 1990-1995 El Ni o- Southern Oscillation event: Longest on record. *Geophysical Research Letters*, **23**, 57-60.
3. Rajagopalan, B., Lall, U., and Cane, M.A., 1997. Anomalous ENSO occurrences: an alternate view. *Journal of Climate*, **10**, 2351-2357
4. Wyrtki, K, and Kilonsky, B., 1984. Mean water and current structure during the Hawaii to Tahiti shuttle experiments. *Journal of Physical Oceanography,* **14**, 242-254
5. Zebiak, S.E., and Cane, M.A., 1991. Natural climate variability in a coupled model, pp. 457-470, Elsevier, New York.
6. Deser C., M.A. Alexander and M.S. Timlin, 1996. Upper-ocean thermal variations in the North Pacific during 1970-1991, *J. Climate*, **9**, 1840-1855.
7. Gu, D., and Philander, S. G. H., 1997. Interdecadal climate fluctuations that depend on exchanges between the tropics and extratropics. *Science* **275**, 805-807.
8. Zhang, R.H., L.M. Rothstein and A.J. Busalacchi, 1998. Origin of upper-ocean warming and El-Nino changes in the tropical Pacific Ocean, *Nature*, **391**, 879-883.
9. Jenkins, W.J., 1996. Studying thermocline ventilation and circulation using Tritium and 3He, paper presented at Maurice Ewing Symposium "*Application of Trace Substance Measurements to Oceanographic Problems,*" AGU, Washington, D.C.,
10. Philander, S. G. H., 1990. *El Ni o, La Ni a, and the Southern Oscillation*, 293 pp., Academic San Deigo, Calif.
11. stlund, H. G., H. Craig, W. S. Broecker, and D. Spencer, 1987: *GEOSECS Atlantic, Pacific, and Indian Ocean Expeditions,* vol, 7, 200 pp., Natl. Sci. Found., Washington, D.C.
12. Key, R. M., *et al.*, 1996: WOCE AMS radiocarbon I: Pacific Ocean results (P6, P16, and P17). *Radiocarbon*, **38**, 425-518.
13. Druffel, E. M., 1981: Radiocarbon in annual coral rings from the eastern tropical Pacific Ocean, *Geophys. Res. Lett.*, **8**, 59-62.
14. Toggweiler, J. R., K. Dixon, and W.S. Broecker, 1991: The Peru upwelling and the ventilation of the South Pacific thermocline, *J. Geophy. Res.*, **96**, 20467-20497.
15. Schrag, D. P., 1999. Rapid analysis of high-precision Sr/Ca ratios in corals and other marine carbonates. *Paleoceanography*, **14**, 97-102.
16. Vogel, J. S., J.R., Southon, and D.E. Nelson, 1987: Catalyst and binder effects in the use of filamentous graphite for AMS. *Nuclear Instruments and Methods in Physics Research, Sect.B*, **29**, 50-56.
17. Davis, J. C., *et al..*, 1990: LLNL/UC AMS facility and research program. *Nuclear Instruments and Methods in Physics Research*, Sect. B, **52**, 269-272.
18. Stuiver, M., and H. A. Polach, 1977: Discussion and reporting of 14C data. *Radiocarbon*, **19**, 355-363.

19. Dodge, R. E., and J. R. Vaisnys, 1980: Skeletal growth chronologies of recent and fossil corals, in *Skeletal Growth of Aquatic Organisms,Top. Geobiology* vol. 1, edited by D. C. Rhoads and R. A. Lutz, pp. 493-517, Plenum, New York.
20. Fairbanks, R.G., and D. Dodge, 1979: Annual periodicity of the 18O/16O and 13C/12C ratios in the coral *Montastrea annularis, Geochim. Cosmochim. Acta,* **43**, 1009-1020.
21. Guilderson,T.P., and D.P. Schrag, 1999. Reliability of Coral Records from the Western Pacific Warm Pool: A Comparison Using Age-Optimized Records. *Paleoceanography*, 14, 457-464.
22. Guilderson, T.P., D.P. Schrag, M. Kashgarian, and J. Southon, 1998: Radiocarbon Variability in the Western Equatorial Pacific Inferred from a High-Resolution Coral Record from Nauru Island. *J. Geophys. Res.,* **103**, 24641-24650.
23. Guilderson, T.P., and Schrag, D. P., 1998: Abrupt shift in subsurface temperatures in the Eastern Tropical Pacific associated with recent changes in El Ni o. *Science*, **281**, 240-243.
24. Guilderson, T.P., *et al,* 2000a: Southwest subtropical Pacific surface radiocarbon in a high-resolution coral record. *Radiocarbon*, **42**, 249-256.
25. Brown, T. A., G. W. Farwell, P. M. Grootes, F. H. Schmidt, and M. Stuiver, 1993. Intra-annual variability of the radiocarbon content of corals from the Galapagos Islands, *Radiocarbon* **35**, 245-251.
26. Moore, M. D., D. P. Schrag, and M. Kashgarian, 1997. Coral radiocarbon constraints on the source of the Indonesian throughflow, *J. Geophys. Res.*, **102**, 12,359-12,365.
26. Moore, M. D., D. P. Schrag, and M. Kashgarian, 1997. Coral radiocarbon constraints on the source of the Indonesian throughflow, *J. Geophys. Res.*, **102**, 12,359-12,365.
27. Rodgers, K.B., D.P., Schrag, M.A., Cane, and N.H., Naik, 2000: The bomb C-14 transient in the Pacific Ocean, *J. Geophys. Res.*, **105**, 8489-8512.
28. Guilderson, T.P., K. Caldeira, and P.B. Duffy, 2000. Radiocarbon as a diagnostic tracer in ocean and carbon cycle modeling. *Global Biogeochem. Cycles*, **14**, 887-902.
29. England, M.H., and S. Rahmstorf, 1999. Sensitivity of ventilation rates and radiocarbon uptake to subgrid-scale mixing in ocean models, *J. Phys. Oc.*, **11**, 2802-2827.

FORM B
IAEA-CN-80

INTERNATIONAL ATOMIC ENERGY AGENCY

International Conference on the
Study of Environmental Change Using Isotope Techniques

23 - 27 April 2001
Vienna, Austria

To be sent to competent official authority (Ministry of Foreign Affairs, national atomic energy authority) for transmission to the International Atomic Energy Agency, Vienna International Centre, Wagramer Strasse 5, P.O. Box 100, A-1400 Vienna, Austria, [Telefax no. +43-1-26007]

FORM FOR SUBMISSION OF A PAPER

TITLE OF THE PAPER:

Biogeochemical proxies in scleractinian corals used to reconstruct ocean circulation

AUTHOR(S) INITIAL(S) AND FAMILY NAME(S)	SCIENTIFIC ESTABLISHMENT(S) IN WHICH THE WORK HAS BEEN CARRIED OUT	TOWN/COUNTRY
1. T.P. GUILDERSON	CENTER FOR AMS, LAWRENCE LIVERMORE NATIONAL LABORATORY	LIVERMORE CA USA
2. M. KASHGARIAN	CENTER FOR AMS, LAWRENCE LIVERMORE NATIONAL LABORATORY	LIVERMORE CA USA
3. D.P. SCHRAG	HARVARD UNIVERSITY	CAMBRIDGE MA USA
4.		

AUTHOR WHO WILL PRESENT THE PAPER

MR./MS. DR

INITIAL(S): T.P.

FAMILY NAME: GUILDERSON

MAILING ADDRESS:
CENTER FOR AMS
UC/LLNL L-397
7000 EAST AVENUE
LIVERMORE CA 94551 USA

FOR URGENT COMMUNICATIONS PLEASE INDICATE:

TELEFAX NO.: 9254237884 TELEPHONE NO.: 9254221753

E-MAIL: GUILDERSON1@POPEYE.LLNL.GOV

I hereby agree to assign to the International Atomic Energy Agency

G the Copyright or

G the Non-Exclusive, Royalty-Free License (this option is only for those authors whose parent institution does not allow them to transfer the copyright for work carried out in that institution)

to publish the above-mentioned paper, and certify that no other rights have been granted which could conflict with the right hereby given to the Agency.

Date: (Signature of Main Author)